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FINAL REPORT

Manufacture of a Sensitive Angle Measuring System

Contract NAS 5-9383

Prepared for:
National Aeronautics and Space Administration
Goddard Space Flight Center
Magnetic Gradient Free Facility
Greenbelt, Maryland

FAIRCHILD HILLER CORPORATION
REPUBLIC AVIATION DIVISION
Farmingdale, New York 11735

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SECTION I

INTRODUCTION

In this contract (NAS 5-9383) the Republic Aviation Division of Fairchild Hiller Corporation undertook to supply a sensitive Angle Measuring System for use by NASA-Goddard Space Flight Center. As the system was to be used in the Magnetic Gradient Free Facility at the Center, the transducer unit was also required to be of a design to maintain its own magnetic disturbance effects to low levels.

To achieve the necessary sensitivity, accuracy, and assist in attaining the low magnetic disturbance figure, Republic applied the capacitive motion sensing principle that they had successfully developed for other applications.

The system is required to deliver a minimum voltage output for a given angular displacement. A calibration system was developed to demonstrate this and was subsequently also included as part of the deliverable items. This facilitates the contractual demonstration of the system performance and also remains available for the recalibration of the system by the NASA-Goddard Space Flight Center when installed in test facilities.

The primary objective was to develop a system capable of measuring the small angular displacements resulting from the application of 1 to 3000 dyne-centimeter torques to a system of 3000 dyne-centimeters per arc second stiffness. The specified sensitivity was exceeded by a factor of 30 over the lower one-third of the torque range, exceeded by a factor of 10 over the middle one-third of the torque and exceeded by a factor of 3 over the upper one-third of the torque range. Adjustment of the capacitance gap can still further increase this sensitivity if required.

The accuracy of the system also exceeded the specified figure by a factor of 5 during verification at Republic facilities.

The measurement range of the instrument far exceeds the specified range. The upper limit being over 250 times the specified range. Additionally, adjustment of the capacitance gap can further increase this range.

In all areas, therefore, the instrument considerably exceeds all specifications and has the ability to still further exceed these figures by simple readjustment. The system is seen to be a sensitive yet flexible, and a rugged instrument for the accurate determination of angular displacement in the Gradient Free Facility.

SECTION II

GENERAL DESCRIPTION

The angular displacement meter is based upon the capacitive linear displacement transducer developed by Republic and used as an important component in a sensitive thrust measuring system already supplied to Goddard Space Flight Center.

The principle of the displacement measuring unit is based upon two back-to-back capacitors whose complementary out-of-balance is detected by means of an A.C. bridge circuit. The configuration of the angular displacement transducer is illustrated in Figure 1 and the schematic for the bridge circuit is depicted in Figure 2. The working drawings for these two areas are covered by PC059D0000 and PC059D0001 respectively.

The illustration shows that the transducer consists of two plates: one is a base plate, and the other a plate carried by the test package or its mounting. The two plates are centralized with reference to each other by the flexure pivot bearings shown. These pivots are friction free but do contribute some resistance to torsional motion. The pivots are therefore chosen to contribute insignificant restraint to the system.

The transducer was first constructed of a woven glass fabric-epoxy resin plastic with high mechanical strength. The capacitance plates were of the same material, appropriately coated with silver conductive paint. During the course of test and calibration, transducer drift was experienced. This unit was reproduced using aluminum throughout the construction except at the capacitance plates, and the drift condition was corrected.

The capacitance change is read by a bridge system, the operation of which falls into two modes. For general angle monitoring the angle deflection is read directly on center zero indicator meter or a recorder. The best range being selected for the deviation obtained. For more precise measuring the bridge is balanced by a voltage from an accurate voltage divider acting on the bridge

Figure 1. Angle Measuring System

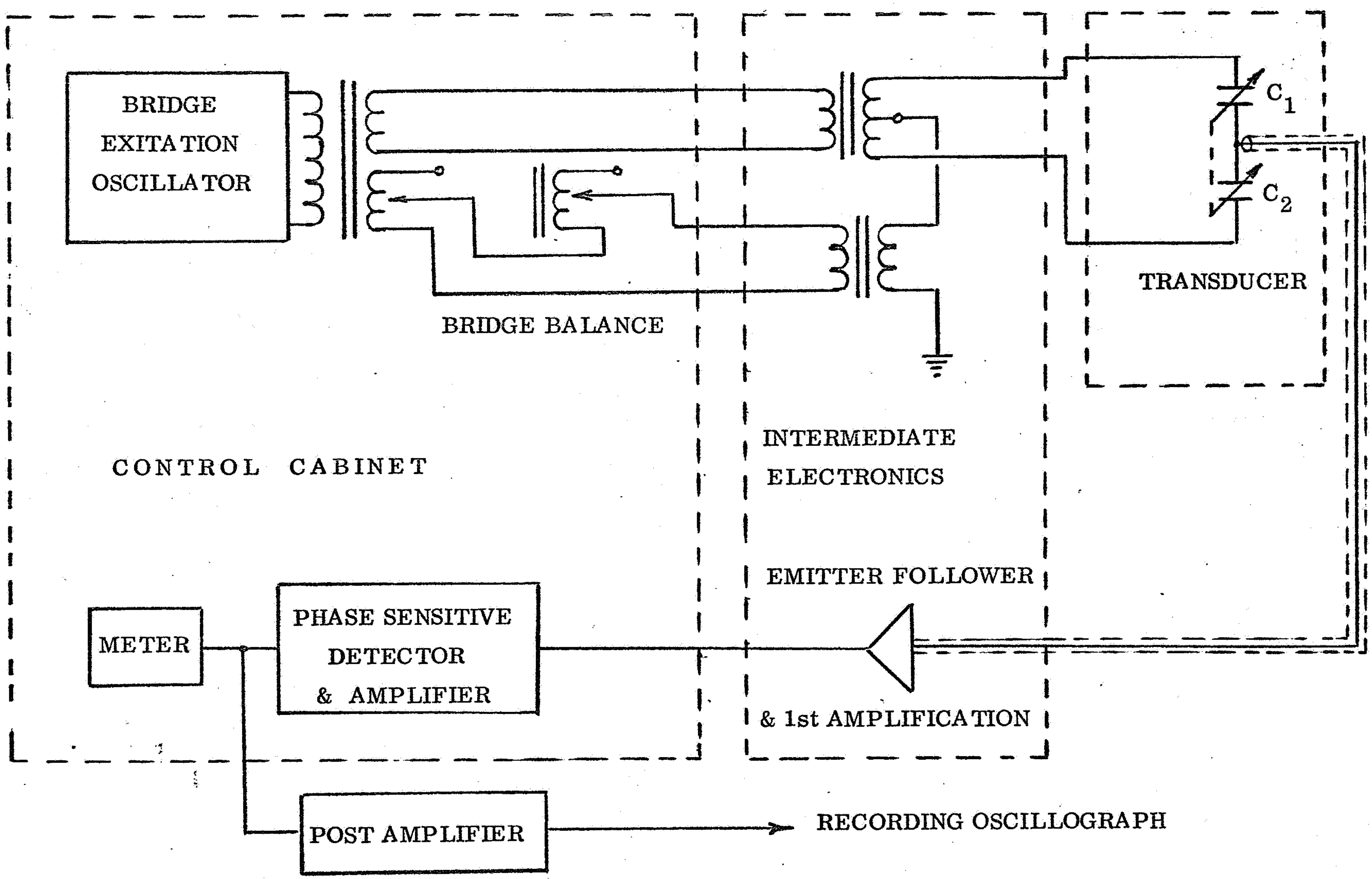

Figure 2:. System Schematic

driving voltage. The balancing voltage is, in essence, a negative feedback of the bridge voltage, the ratio of this feedback being a reading of the capacitance unbalance. In this mode the accuracy is independent of the bridge voltage and amplification of the system and is a function of the meter zero and the divider accuracies.

The construction of the transducer is non-magnetic in nature and in any case complies with the requirement of its magnetic disturbance being less than 100 gamma at four-feet distance. The level of the magnetic disturbance caused by the transducer head has been verified by a magnetometer reading as 10 gamma at 1.0 foot.

In addition to the transducer head and the control station, an intermediate electronics package is included into the connecting cables to maintain the signal from the transducer at suitable levels over long cables. The intermediate head is located at 4 feet from the transducer head and is capable of operation in vacuum at 10^{-6} torr. The magnetic disturbance caused by this head is again small and has been verified as 10 gamma at 3 feet from the intermediate package.

SECTION III

SYSTEM PARAMETERS

The measuring requirements of the specification state a range of 0.01 to 1.0 arc-second with an accuracy of ± 1% of full scale. The 1% accuracy implies a resolution of less than 1% of full range, i.e., less than .01 arc-second; which can be established conveniently at .0025 arc-second. With the capacitor plates centered at 1.5 inches radius from the main pivot of the transducer the .0025 arc-seconds results in a displacement of 1.83×10^{-8} inches at the plates.

Therefore, the resolution of one-quarter percent of the full range of 1.0 arc-second establishes that a motion of 1.83×10^{-8} inches be resolved at the capacitor plates. The motion at the plates for the full 1.0 arc-second excursion is consequently 7.32×10^{-6} inch.

The system specification calls for an output of 1 m-volt into a 600 ohm load per dyne-cm applied to the complete torque measuring system, with the stiffness of the overall system stated as 3000 dyne-cm per arc-second. The sensitivity of the Angle Measuring System is therefore established at 3.0 volts per arc-second (or, per 7.32×10^{-6} inches displacement at the plates).

The basic electronic bridge circuit provides an output of 1.0 m-volt for a deflection of 1% of theoriginal gap in the transducer, at the lowest gain setting. At the highest gain the output is 3.0 volts for the same 1% displacement. This overall variation in gain is divided into 8 ranges, with the sensitivity of each second range 10 times the previous. Thus, Range No. 6 is 10 times more sensitive than the least sensitive Range No. 8, Range No 4 is 100 times Range No. 8 and Range No. 2 is 1000 times Range No. 8. Each odd range is 3 times more sensitive than the previous; Range No. 7 being 3 times Range No. 8, Range No. 5 being 30 times Range No. 8, and so up to Range No. 1 which is 3,000 times Range No. 8.

The choice of the No. 4 range (100 mV/1% change in gap) and the establishment of .002 inch original gap will be seen to give a suitable system in conjunction with a d.c. post amplifier.

For the 1 arc-second motion the 7.32×10^{-6} inch deflection represents 0.365% change of the 0.002 inch gap at the plates. In the No. 4 range this is 0.365 of the full scale 100 m-volt output, or 36.5 m-volt. By using the Special Scale position on the Control Panel this output figure is adjusted to become 30.0 m-volts. The use of a 100 to 1 post amplifier (Incor Model 114) then brings this output to the specified 3.0 volts per arc-second.

However, the system has more capability for use at the smaller angles. Ranges No. 3, 2, and 1, provide sensitivities of 9 volts, 30 volts, and 90 volts per arc-second respectively. It should be noted, however, that the circuit is such as to limit the output to 10.0 volts (100 millivolts before the post amplifier) in each range. Thus, Range No. 4 is limited to a maximum angle of approximately 3 arc-seconds, Range No. 3 to 1 arc-second, Range No. 2 to one-third arc-second, and Range No. 1 to one-tenth arc-second; - each, of course, at their respective sensitivities.

Additionally the other ranges, No. 5, 6, 7, and 8, are available for the measurement of larger angles; Range No. 5 for up to approximately 9 arc-seconds at 1.0 volt per arc-second, Range No. 6 for 30 arc-seconds at 0.3 volts per second, Range No. 7 for 90 arc-seconds at 0.1 volt per second and Range No. 8 for up to 270 arc-seconds at 0.03 volts per second. The last range being limited to 270 arc-seconds (approximately 4-1/2 minutes) by the .002 inch total motion available at the capacitor plates.

In summary then, the system measures from 0 to 4-1/2 minutes of arc in 8 ranges, with sensitivities from 0.1 volt per arc-second to 90 volts per arc-second. The latter occurring in the range with a resolution of about 5×10^{-5} arc-second.

SECTION IV

CALIBRATION EQUIPMENT

To calibrate the Angle Measuring System and verify its performance, two additional pieces of equipment are required: Inertia Plates , and a calibrator unit.

The means of accurately and repetitively producing the small angles necessary to verify the performance of the angle measuring system are limited in number; particularly bearing in mind the requirement of ± 1/100 arc-second accuracy if the capability of the system is to be checked to ±1%. One practical method of producing the small angles is to determine the torsional stiffness of the system and then apply dead-weight torques to the transducer; this is the method utilized for the verification here.

The stiffness of the system may be determined by calculating the intertia, I, of the transducer, setting the unit oscillating to establish the torsional natural frequency, ω, and deriving the stiffness, K, from the expression:

$$\omega = \sqrt{\frac{K}{I}}$$

To enable this method of measurement to be practical, however, two additions must be made to the transducer. First, as described earlier the transducer stiffness is low, less than 5-dynes-cm/arc-second. In this circumstance the torque to produce the small angular displacements would be impractically low to produce accurately. The calibrator is therefore equipped with an additional flexure pivot to represent the stiffness of the overall torque measuring system to which the transducer will be applied. For convenience one pivot is utilized and only approximates the torquemeter stiffness, providing a stiffness of 2212.5 dyne-cm/$\widehat{sec}$ as opposed to the real system stiffness of 3000 dyne cm/$\widehat{sec}$. However, this enables a weight of .79 gms to produce a calibrating 1 arc-second, instead of about .79 milligrams for the transducer stiffness alone.

The second addition required is an Inertia Plate. The inertia of the moving section of the transducer alone is low and of a shape difficult to calculate with absolute accuracy. A large, flat round plate is therefore added to the moving section of the transducer. The inertia of the plate can be accurately calculated and the plate is sized such that the inertia of the transducer is small compared to the plate. Any inaccuracy between the transducer calculated inertia and its real inertia will be very small compared to the overall inertia. Additionally, plates of other material and thicknesses are utilized singularly and compounded to establish stiffness measurements at various conditions.

The calibrator with an inertia plate and calibration weight is shown in Figure 3. The calibrator is shown in Republic Drawing PC059D0002.

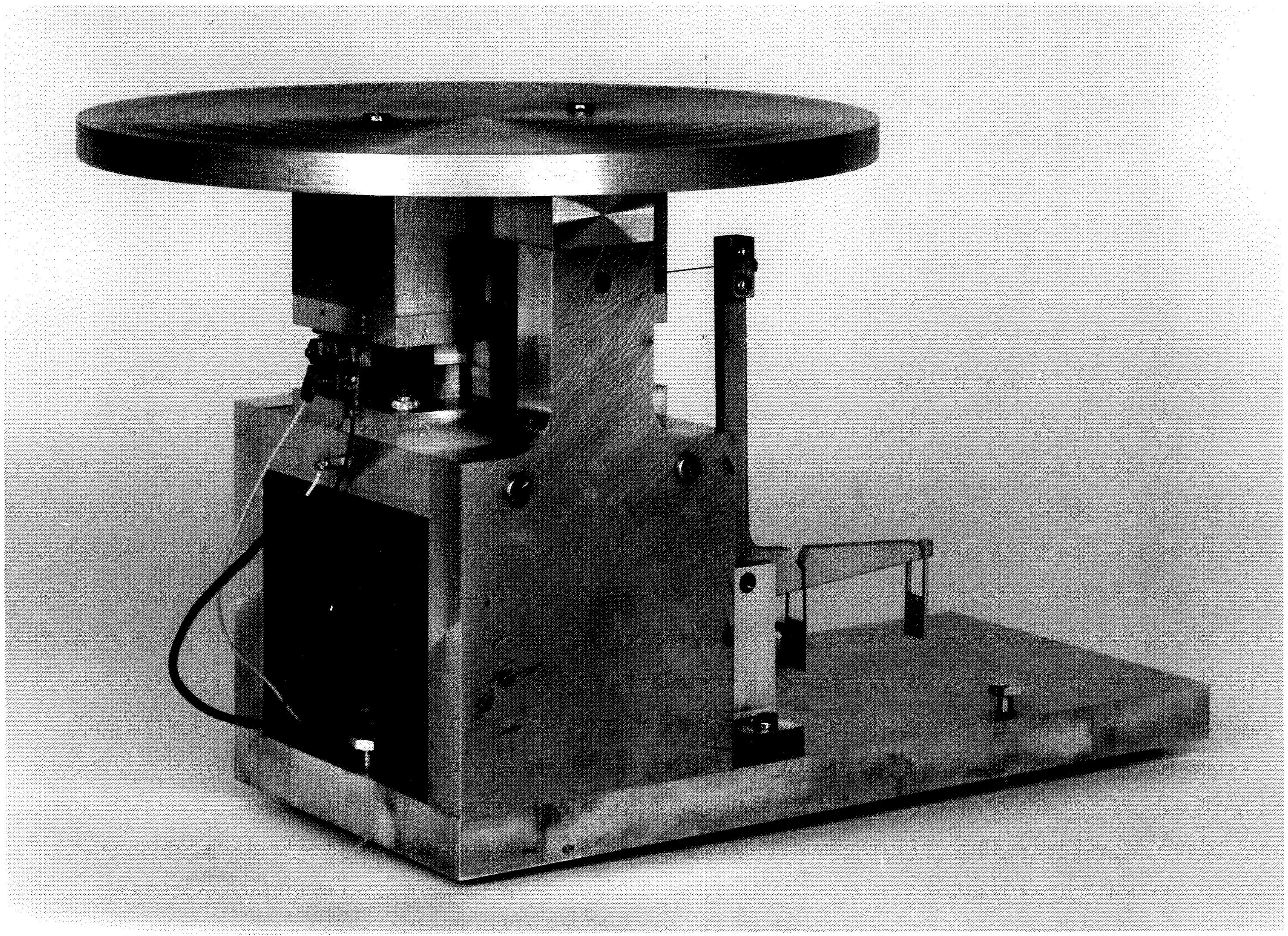

Figure 3. Calibration Equipment

SECTION V

SYSTEM VERIFICATION AND CALIBRATION

A. MAGNETIC DISTURBANCE

The magnetic disturbance of the transducer alone and the intermediate electronics alone were first established. Republic's gradient free facility was used in conjunction with a Republic Model RGD 100 gradiometer.

The disturbance due to the transducer was determined to be no more than 10 gamma at one foot from the center of the transducer in all directions. That due to the electronics was determined as no more than 10 gamma at three feet from the center of the package in all directions. Both figures are one order better than the specification disturbance at 4 foot distance.

B. ANGLE MEASURING

The transducer was assembled into the calibration unit as shown in Figure 3. Three different Inertia Plates were attached to the unit first singularly and finally as a compounded plate. The characteristics of the plates and the measured and derived parameters to establish the effective stiffness of the calibration-transducer assembly are shown in Table V-1.

NOTE: The column noted as Transducer Inertia is in fact a combination of the transducer moving section (.0001385 slug ft^2) and the mounting section (.0005595 slug ft^2) common to the attachment of all Inertia Plates.

To obtain the natural frequency at the various inertia conditions the transducer with an Inertia Plate, or Plates, attached was set oscillating with the system output driving an oscilloscope. The natural frequency thus displayed was first noted at higher amplitude and then at lower amplitude; to ensure no change in frequency, and thus effective stiffness, at the very small displacements. Three readings were then taken and photographed on the oscilloscope for each plate, or plate assembly.

TABLE V-1

Plate No.	Size inches	Material	Weight lb.	Plate Inertia Slug ft^2	Transducer Inertia Slug ft^2	Total Inertia	Measured Frequency Hz	ω^2 (rad^2)	K (lb ft/rad)
1	10 Dia. x $\frac{1}{2}$	Aluminum	3.7595	0.010147	0.000698	0.010845	8.88	3109.85	33.7363
2	10 Dia. x $\frac{1}{4}$	Steel	5.7084	0.015407	0.000698	0.016105	7.28	2090.17	33.6622
3	10 Dia. x $\frac{1}{2}$	Steel	10.8981	0.029414	0.000698	0.030112	5.32	1116.23	33.6119
1+2+3	10 Dia x $1\frac{1}{4}$	Aluminum & Steel	20.3660	0.054967	0.000698	0.055665	3.92	605.99	33.7324

Stiffness (mean) K_m = 33.6832 lb ft/rad.

= 404.16 lb in/rad.

= 0.889 gram inches/sec

These records were then analyzed and compared to obtain a natural frequency, which is reported in the table for each inertia condition.

The mean stiffness derived from these measurements is seen to be 33.6832 lbs-ft/rad, 404.16 lb-in/rad (or 2212.5 dyne-cm/arc-second), with all the stiffnesses falling within about ± 2/10 of 1% of the mean. The stiffness thus obtained is accurate for proving the system to within ± 1% of full scale.

Utilizing this effective stiffness figure and with knowledge of the calibrator geometry, which shows that the calibration force is applied at a radius of 1.5 inches from the pivot line of the transducer, the weight required on the 4-inch to 3-inch bell-crank lever to produce a 1 arc-second displacement was calculated.

(It should be noted that the flexure pivot supporting the bell-crank lever is not included in the derived system stiffness figure, K_m. However, this pivot is a Bendix 6008-800 unit with a stiffness of approximately 0.041 lb-in/rad. This is less than 0.01 of 1% of K_m; additionally, it is additive to K_m, so that the angular displacement derived is in any case conservative).

$$\text{Stiffness } K_m = 33.6832 \ \frac{\text{lb ft}}{\text{rad}} = .889 \ \frac{\text{gram-inch}}{\text{sec}}$$

$$\text{Weight} = \frac{.889}{1.5} \times \frac{4}{3} = .790 \text{ grams}$$

The actual weight produced is .7915 grams ± .0015, which is within ± 0.2% of the one second full range.

To produce a 0.333 arc-second deflection, this weight is applied at a second, in-board position on the bell-crank lever to provide a ratio of 4:1. A second weight is also provided which is one-third of the first weight (actual weight 0.262 grams, ± .0015). These two weights in combination at the two positions on the lever produce these actual angular deflections in arc-seconds: 0.1106 seconds, 0.3340, 0.4446, 0.6656, 1.0019, and 1.3335 seconds. The weights were produced to within ± 2 milligrams (checked on a laboratory balance) so may be taken as secondary standards for calibrations of the system to ± 1% of full range and are actually accurate to produce each deflection to within one-half of 1%.

The specified range 0.01 to 1.0 arc-seconds is therefore adequately covered to demonstrate linearity. If necessary other weights can be easily produced to prove any or all other ranges as required.

The system was verified in its No. 4 Range (0-1 arc-second, 0-3.0 volts) and the results are shown in Table V-2. The measurements were obtained, with the output of the post amplifier monitored by a digital voltmeter, to an accuracy of ± .01% on the measurements stated.

The table indicates the accuracy of the system to be about ± 2 millisecond (2/10 of 1% of an arc-second) or ten times the specified accuracy. This figure is also seen to include linearity and repeatability, being the average of six consecutive readings compared to a calculated, linear ideal response. The maximum error read within the one second range is seen to be approximately 4 millisecond (0.4%), again well within specifications.

All these measurements were obtained under less than ideal conditions for the use of such an accurate instrument. In all probability some of the larger inaccuracies, although still small, may have been produced by physical disturbances in the general laboratory area. Performance of the instrument in an isolated area can be expected to improve over the already very adequate results.

During the course of development work considerable drift of the first epoxy-glass transducer unit was experienced. Absence of drift in the electronic circuits was established by the utilization of fixed capacitors to replace the transducer plates.

It was theorized that two mechanisms could produce the drift in the transducer elements. First, the insulating properties of the epoxy-glass plastic could support thermal gradients within the unit, these being only slowly equalized. Second, local stresses were produced in the unit, say at the fluxure pivots, which gave rise to creep strain in the plastic material; a process which has been encountered in other sensitive systems incorporating thermoplastic materials.

The transducer unit was therefore reproduced in aluminum and the drift was practically eradicated. Long term drift was established as no more than 3.0 milli-seconds, (< 1/2 of 1% of full range) per hour, again under less than ideal conditions.

TABLE V-2

Applied Angle Arc-secs.	0.1106		0.3340		0.4446		0.6656		1.0019		1.3335	
Theoretical Linear Output (3.0 Volts/$\widehat{sec}$) Volts	0.3318		1.0020		1.3338		1.9968		3.0057		4.0062	
	Actual Output Volts	Error % of $\widehat{sec}$.	Actual Output Volts	Error % of $\widehat{sec}$.	Actual Output Volts	Error % of $\widehat{sec}$.	Actual Output Volts	Error % of $\widehat{sec}$.	Actual Output Volts	Error % of $\widehat{sec}$.	Actual Output Volts	Error % of $\widehat{sec}$.
Reading 1	0.340	+ 0.27	1.013	+ 0.37	1.330	- 0.13	1.999	+ 0.07	3.001	- 0.15	4.005	- 0.03
2	0.332	+ 0.01	0.999	- 0.10	1.330	- 0.13	1.996	- 0.02	3.019	+ 0.44	4.030	+ 0.59
3	0.334	+ 0.07	0.999	- 0.10	1.330	- 0.13	1.998	+ 0.04	3.009	+ 0.11	3.992	- 0.35
4	0.333	+ 0.04	0.999	- 0.10	1.339	+ 0.17	1.996	- 0.02	3.000	- 0.19	3.995	- 0.27
5	0.326	- 0.19	0.999	- 0.10	1.335	+ 0.04	1.989	- 0.26	3.001	- 0.15	3.995	- 0.27
6	0.324	- 0.26	1.024	+ 0.73	1.342	+ 0.27	1.987	- 0.33	3.000	- 0.19	3.995	- 0.27
RMS Error	.0053	0.18	0.010	0.33	0.0048	0.16	.0053	0.18	.0068	0.22	0.011	0.36
Mean Reading	0.332	0.01	1.005	0.10	1.334	0.01	1.994	0.14	3.005	0.02	4.002	0.10